UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

IS A FLEX-GRID OPTICAL NETWORK WORTHY?

A Degree Thesis

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Abstract

Applying flexibility to the optical networks has become a hot topic in the optical technologies field. This proposal has some advantages but also considerable drawbacks that allow us to question if the use of these networks would be worthy. So this is the aim of this thesis: testing different type of optical networks configurations in order to prove whether the application of flexibility is worthy or not.

The use of flexible networks has a very positive impact in terms of efficiency, which is possible because a flexible configuration only uses the spectrum needed in every single connection. On the other hand, the different size of the connection as well as the randomness of its duration results in a highly fragmented spectrum which results in a greater blocking probability than the one obtained with Fixed-Grid networks, as has been proved with the simulations done in this project and whose results will be shown in this thesis.

Resum

L'aplicació de flexibilitat a les xarxes de fibra òptica s'ha convertit en un tema de gran interès en el camp de les tecnologies òptiques. Aquesta proposta disposa d'una gran quantitat d'avantatges així com de desavantatges considerables que posen en dubte la seva vàlua. Aquest és, per tant, el principal propòsit d'aquest projecte: testar diferents tipus de configuracions de xarxa òptica per concloure si val la pena o no aplicar flexibilitat.

L'ús de xarxes flexibles té un impacte positiu pel que fa a la eficiència, ja que en una configuració flexible només es fa ús de l'espectre necessari per cada connexió. Per altra banda, la variabilitat de mida de connexió juntament amb la aleatorietat de la connexió provoca una gran fragmentació de l'espectre que acaba suposant en un augment de la probabilitat de bloqueig tal i com hem demostrat en les simulacions fetes en aquest projecte i que es mostraran en aquesta tesi.

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Resumen

Aplicar flexibilidad en redes de fibra óptica es uno de los temas que despierta más interés en el campo de las tecnologías ópticas. Esta propuesta presenta una gran cantidad de ventajas así como algunas desventajas de consideración que hacen dudar acerca de su validez. Éste es el objetivo principal de este proyecto: probar distintas configuraciones de red óptica con el objetivo de concluir si vale la pena o no el uso de flexibilidad.

El uso de redes flexibles presenta unas prestaciones muy positivas en cuanto a eficiencia, eso se debe a que una configuración flexible solo usa el espectro que se precisa para cada conexión. Por otro lado, la variabilidad de tamaño de conexión junto con la aleatoriedad de su duración provoca una gran fragmentación del espectro con lo que la probabilidad de bloqueo se incrementa, así se ha demostrado con las simulaciones de este proyecto cuyos resultados se mostrarán en esta tesis.

Pels de sempre

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I would like to specially thank the director of this project: Jaume Comellas. Jaume has been a very important person during these months; not only with his advices and knowledge I have been able to carry on with this project when I was in trouble, but I also have enjoyed the interesting conversations we kept after our meetings. Moreover, I would also like to thank Joan Manuel Gené for his excellent treatment.

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Table of contents

Abstract 1
Resum 2
Resumen 3
Acknowledgements 5
Revision history and approval record 6
Table of contents 7
List of Figures 9
List of Tables: 10
1. Introduction 11
1.1. Inception 11
1.2. Statement of purpose, requirements and specifications 11
1.3. Work Plan 12
1.3.1. Work Packages 12
1.3.2. Gantt Diagram 14
1.3.3. Incidences 14
2. State of the art of the technology used or applied in this thesis: 15
2.1. Elastic Optical Networks 15
2.1.1. EON architecture 15
2.2. EON's advantages: spectrum's efficiency 16
2.2.1. EON's drawbacks: spectrum's fragmentation 17
3. Methodology / project development: 18
3.1. Simulator 18
3.2. Network Topologies 19
3.3. Connection parameters 19
3.3.1. Defining the route 19
3.3.2. Duration of the connections. 20
3.4. Fixed-Grid strategy 20
3.4.1. Fixed-Grid strategy: connection allocation 20
3.4.2. Fixed strategy: connection partition 22
3.4.3. Justice in a partition 23
3.5. Statistical distribution 23

3.6. Assignment policy: reallocation, allocation and tear down 24
3.6.1. Reallocation policy....24
3.6.2. Allocation policy....25
3.6.2.1. Spectrum's treatment 25
3.6.2.1.1. Flex-Grid strategy....26
3.6.2.1.2. Fixed-Grid strategy....26
3.6.3. Temporal treatment: tear down management 26
3.7. Obtaining results 27
3.7.1. Justice considerations 28
3.7.2. Improving the conditions....28
4. Results 29
4.1. Results for the Uniform distribution....29
4.2. Results for the Gaussian distribution 32
4.3. Results for the beneficial Gaussian distribution 35
4.4. Final considerations 38
5. Budget....40
6. Conclusions and future development:....41
Bibliography:....42
Appendices (optional):....43
Glossary 44

List of Figures

Figure 1: Gantt Diagram 14
Figure 2: EON architecture 15
Figure 3: Status of a 20 FS spectrum window in an exemplary link....................17
Figure 4: NSFnet topology 19
Figure 5: EON topology 19
Figure 6: Incompatibility between a connection larger than 4FS and a 4FS strategy spectrum....................20
Figure 7: BP comparison in an EON topology for a uniform distribution 31
Figure 8: BP comparison in an EON topology for a uniform distribution 31
Figure 9: BP comparison in an EON topology for a Gaussian distribution 34
Figure 10: BP comparison in an EON topology for a Gaussian distribution 34
Figure 11: BP comparison in an EON topology for a Gaussian distribution 37
Figure 12: BP comparison in an EON topology for a Gaussian distribution 37

List of Tables:

Table 1: Work Packages and tasks....14
Table 2: Efficiencies' comparison per type of connection in a uniform distribution 16
Table 3: Spectrum assignment model for 4FS and 5FS strategies....21
Table 4: Partition strategy results....22
Table 5: Gaussian beneficial parameters....24
Table 6: Allocation results for uniform distribution....29
Table 7: Results of the beneficial decisions for uniform distribution 30
Table 8: Summary for the EON topology (uniform) 32
Table 9: Allocation results for Gaussian distribution....32
Table 10: Results of the beneficial decisions for Gaussian distribution 33
Table 11: Summary for the EON topology (Gauss)....35
Table 12: Allocation results for a beneficial Gaussian distribution....35
Table 13: Results of the beneficial decisions for a beneficial Gaussian distribution 36
Table 14: Summary for the EON topology (beneficial Gaussian) 38
Table 15: Budget 40

1. Introduction

1.1. Inception

This project was born as a continuation of the work previously done by Jaume Comellas and Gabriel Junyent. This work is about Flex-Grid ON, whose main concepts will be introduced in next sections. Concretely, it consists on a set of simulations that must be done in order to complete the paper [1] by evaluating the case where the completely flexible network is changed by another one where the connections are fixed to 5FS and 4FS respectively.

In order to do so, Jaume provided me with his original algorithm that tested the Blocking Probability (BP) per Offered Load (OL) of a completely flexible network. From this algorithm I have developed the code to test the network for the other sizes of connections previously explained.

1.2. Statement of purpose, requirements and specifications

The purpose of this project is to demonstrate that an Elastic Optical Network (EON) can improve its performance (in terms of Blocking Probability versus Offered Load) by limiting the bandwidth flexibility of the requested connections. This will result in a reduction of the number of useless spectrum voids so it could be possible to obtain some extra gain at the cost of losing some flexibility (which represents some drawbacks). Specifically, my work will consist on testing the performance when we fix the size of the connections, represented by the number of frequency slots (FS) used, to 5FS and 4FS and comparing it to the case when a total flexibility is used in order to see if this totally flexible configuration is worthy or not.

The project main goals are:

- Introducing to the given software the code required to test the channel performance when the size of the connections is limited to 5FS and 4FS respectively.
- Once the code has been introduced, test its operation in terms of BP per OL.
- Find out a statistical distribution for the size of the connections which could provide even a better BP performance that the ones tested before.
- Discuss about the real worthiness of Flex-Grid networks.

1.3. Work Plan

1.3.1. Work Packages

Part 1: Introduction and planning	WP ref: (WP1)	
Major constituent: Planning	Sheet 1 of 5	
Short description: Defining the objectives of the project, groups of tasks, time plan, weekly working schedule, and communication plan. Elaborate and deliver the Project Proposal and Workplan.	Planned start date: 19/02/2015 Planned end date: 06/03/2015	
Internal task T1: Develop Work Plan & Define objectives		

Part 2: Study and analysis of the given resources	WP ref: (WP2)	
Major constituent: Pre Analysis	Sheet 2 of 5	
Short description: Read and understand the paper "Improving Link Spectrum Utilization in Flex-Grid Optical Networks" in order to have a critical view about the EONs. Analysing the Matlab code provided by the director in order to implement later the new functionalities.	Planned start date: 24/02/2015 Planned end date: 09/03/2015	
Internal task T1: Theoretical study of the EONs. Internal task T2: Study and understand the given Matlab Code.		

Part 3: Programming the simulator	WP ref: (WP3)	
Major constituent: Programming	Sheet 3 of 5	
Short description: Once the analysis of the given Matlab code is done and the technology has been correctly understood I will precede with the elaboration of the new code in order to running then the correspondent simulations.	Planned start date: 10/03/2015 Planned end date: 29/05/2015	
Internal task T1: Program in Matlab the 5FS configuration. Internal task T2: Program in Matlab the 4FS configuration. Internal task T3: Find out a beneficial statistical distribution for the connection size and program it in Matlab.		

Part 4: Simulations and results	WP ref: (WP4)	
Major constituent: Simulating and analysis of the results.	Sheet 4 of 5	
Short description: Run the simulations. Once the simulations are done, extract conclusions from these results. Finally compare its performance with the totally flexible networks.	Planned start date: 18/05/2015 Planned end date: 09/06/2015	
Internal task T1: Run the simulations. Internal task T2: Analysis of the simulations. Internal task T3: Comparison with completely flexible case.		

Part 5: Final Report	WP ref: (WP5)	
Major constituent: Write the final report	Sheet 5 of 5	
Short description: Write up the Final Report of this document.	Planned start date: 10/06/2015 Planned end date: 10/07/2015	
Internal task T1: Develop the Final Report.		

1.3.2. Gantt Diagram

		Name	Duration	Start	Finish
1		**Introduction and Planning**	12 days?	**19/02/15 08:00**	**06/03/15 17:00**
2		Develop Work Plan and define objectives	12 days?	19/02/15 08:00	06/03/15 17:00
3		**Study and analysis of the given resources**	10 days?	**24/02/15 08:00**	**09/03/15 17:00**
4		Theoretical study of the EONs	10 days?	24/02/15 08:00	09/03/15 17:00
5		Study and understand the given Matlab code	10 days?	24/02/15 08:00	09/03/15 17:00
6		**Programming the simulator**	59 days?	**10/03/15 08:00**	**29/05/15 17:00**
7		Program in Matlab the 5FS configuration	59 days?	10/03/15 08:00	29/05/15 17:00
8		Program in Matlab the 4FS configuration	15 days?	09/05/15 07:00	29/05/15 17:00
9		Find out and program a benefitial statistic	8 days?	20/05/15 07:00	29/05/15 17:00
10		**Simulations and results**	17 days?	**18/05/15 07:00**	**09/06/15 17:00**
11		Run the simulations	17 days?	18/05/15 07:00	09/06/15 17:00
12		Analysis of the simulations	17 days?	18/05/15 07:00	09/06/15 17:00
13		Comparison with the EONs case	8 days?	29/05/15 07:00	09/06/15 17:00
14		**Final Report**	23 days?	**10/06/15 08:00**	**10/07/15 17:00**
15		Develop the final report	23 days?	10/06/15 08:00	10/07/15 17:00

Table 1: Work Packages and tasks

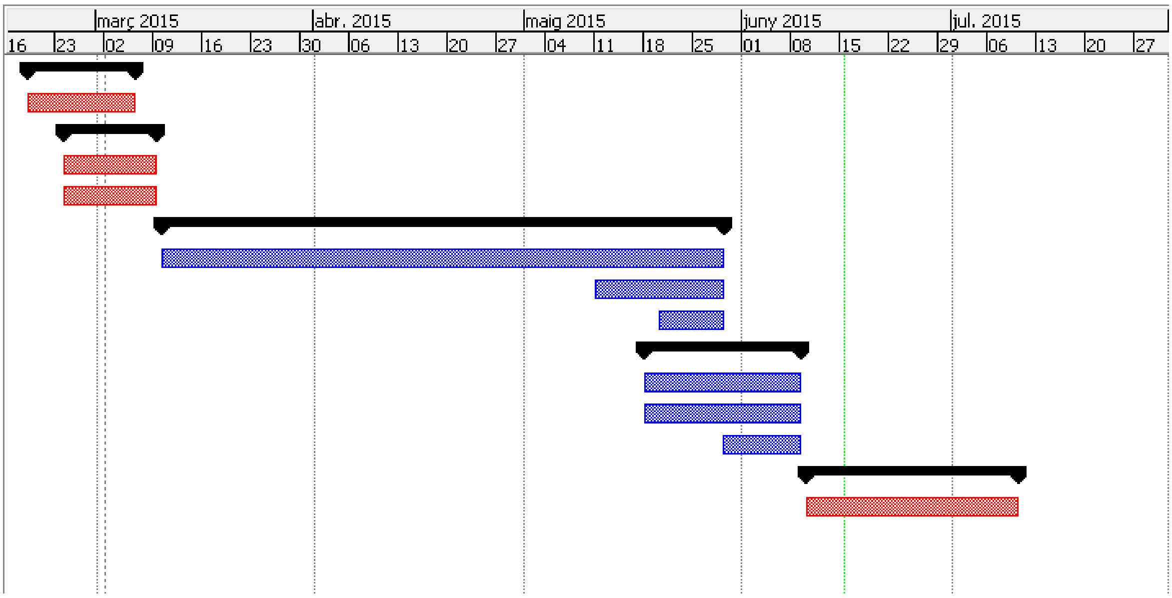

Figure 1: Gantt Diagram

1.3.3. Incidences

The main incidence has been the increase of the time required to finish the Work Package 3. The reason that justifies this increase is that we have added the code necessary to simulate also the 4FS configuration; initially, we were supposed to do only the 5FS configuration. This new configuration has increased the difficulty of the algorithm; as a result, this Work Package has required more time. On the other hand, the first simulations shown extraordinary results which made me realise that there was a mistake in the way that the duration of a connection was processed, which leaded to have shorter connections and consequently obtaining highly better results in terms of BP

2. State of the art of the technology used or applied in this thesis:

The explosion of emerging services such as HD video distribution has pointed out the need of increasing the IP traffic volume, whose growth will have to be exponential. Consequently, network operators will require a new generation of optical transport networks in order to respond to this huge and heterogeneous volume of traffic in a cost-effective and scalable manner. In response to these nowadays needs the EON architecture has been proposed.

2.1. Elastic Optical Networks

As it has been said in the introduction of this section, the EON architecture has been proposed as a response to the large capacity and diverse traffic granularity needs of the future Internet. The conventional WDM network has a rigid grid limit (typically of 50 GHz), this means that regardless of the size of any incoming connection, it will use 50 GHz of the spectrum. On the other hand, an EON architecture allocates the appropriate-sized optical spectrum portion to each connection. Consequently, the incoming connection request can be served in a spectrum-efficient manner. Reaching this spectrum's efficiency is the main achievement of EON architectures; nonetheless, these networks lead to a considerable drawback: spectrum fragmentation, which could have important consequences in terms of an increment of the connections' BP. So as to explain both the advantages and drawbacks of implementing EON networks we will have to describe, firstly, its architecture.

2.1.1. EON architecture

The total available spectrum is divided into constant spectrum units referred as frequency slots (FS), whose typical width is 12.5 GHz. Each FS can carry some amount of traffic depending on the modulation format used and the required reach.

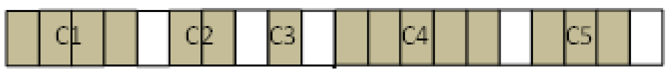

Figure 2: EON architecture

In Figure 2 we can see an example of how we are going to treat an EON architecture in this thesis. A spectrum window of 20 FS is represented and every single box is what we have defined as a FS. This figure represents an example where this spectrum window is occupied by 5 connections whose bandwidth (in FS) is represented by colouring the boxes. An important aspect is that we have to guarantee the separation of the different connections; in order to do so we must leave a free FS between connections, what is known as Guard Band (GB).

2.2. EON's advantages: spectrum's efficiency

Let's prove now that using an EON architecture with complete flexibility improves the efficiency comparing with the case where the connections have a predetermined size of connection; it is important to notice that having a fixed size of connection does not mean that these connections will have always this connection size, we are in an EON architecture and consequently the incoming connections vary following a concrete statistical distribution.

To begin with we have to know the expression that will provide us the Spectrum's Efficiency, assuming a uniform distribution and completely flexible connections:

$$EC = \frac{1}{N}\sum_{n=1}^{N}\frac{n}{n+1}$$

Where "N" is the maximum bandwidth per connection in FS.

When fixing the connections' size to 5FS, we will use the following expression:

$$EC = \frac{1}{N}\left(\sum_{n=1}^{size}\frac{n}{size+1} + \sum_{n=size+1}^{N}\frac{n}{2(size+1)}\right)$$

Where "size" is the fixed connection size. The reason why the expression has changed is that now we are using fixed spectrum spaces (in FS) per every single connection, which mean that every connection regardless of its bandwidth will have to use these predetermined sized spectrum spaces. Therefore, when a connection is larger than the fixed connection size we will have to use more than one connection space in order to allocate the incoming connection. For example, when dividing the spectrum space in blocks of 5FS if the incoming connection has a bandwidth of 6FS we will have to use two of these spectrum divisions, which means having to use 12FS (we have to consider the GBs) to allocate this connection.

Bearing in mind the previous expressions we will obtain the following Spectrum Efficiency results for the different network configurations studied in this thesis:

Type of connection	Spectrum Efficiency
Flex-Grid	0.785
4FS	0.577
5FS	0.555

Table 2: Efficiencies' comparison per type of connection in a uniform distribution

The content of the Table 2 highlights what has been said previously: the efficiency improves considerably when using the Flex-Grid configuration. That happens because in this configuration we only use the part of the spectrum that is strictly needed so as to allocate the connection. The other configurations use more spectrum than the one needed and consequently the efficiency decreases.

2.2.1. EON's drawbacks: spectrum's fragmentation

Once we have proved that using a Flex-Grid configuration has an extremely positive impact on the spectrum efficiency, let's analyze one of its parallel consequences: the fragmentation of the spectrum.

The randomness in the connection setup and tear down processes leads to fragmentation of the spectral resources in the network, especially in dynamic scenarios. As the number of spectrum slots assigned to each connection takes random values (ranging from 1 to 9 FS in this work), the spectrum available in the network links is fragmented into small non-contiguous spectral bands.

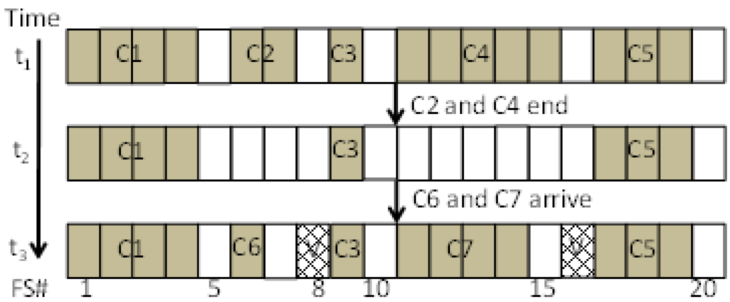

Figure 3: Status of a 20 FS spectrum window in an exemplary link.

Figure 3 represents three different situations in time: In t1 we can observe a completely occupied 20FS spectrum. In t2 the connections C2 and C4 die and in t3 new connections (C6 and C7) replace the space released by C2 and C4. The problem is that the fragmentation of this spectrum, the randomness of the duration in the connection setup and the tear down processes have lead, in this third situation, to a spectrum status where the spaces 8 and 15 are useless spectrum voids. As a result, the probability of finding enough contiguous FSs to allocate incoming traffic demands, especially those traversing multi-hop paths and/or requesting large amounts of bandwidth (BW), is supposed to decrease significantly.

In this thesis we have developed software to test if this theoretical consequence really happens and its real impact in order to be able to create a trade-off between efficiency and BP so as to conclude if a Flex-Grid configuration is really worthy.

3. Methodology / project development:

In this thesis a Matlab code has been elaborated so as to simulate the operation of an optical network when using different spectrum allocation strategies. In this section the main functions and key parameters that have been used in order to programme the Matlab code for each of the network configurations will be explained.

3.1. Simulator

As it has been said, some functions have been programmed in Matlab in order to simulate an optical network under different circumstances. The script that has to be run in order to obtain the results is called `simul_totDef`. This script performs the simulation of each type of network and provides its BP depending on some input values:

- `numconex`: number of connections that are going to be used in the current simulation.
- `tamany_con`: size of the blocks (Flex-Grid, 4FS or 5FS) that are used to divided the spectrum so as to allocate the incoming connections.
- `KSP`: K Shortest Path. Number of times that we will use the Dijkstra's algorithm to find the connections' optimum path in a global network.
- `numslots`: number of FS that represent the whole spectrum. Typical value `numsolots`=160 (because an spectrum occupies 2 THz and the FS is supposed to have a bandwidth of 12.5 GHz)
- `max_bandwidth`: defines the possible maximum size per connection. Typical value `max_bandwidth`=9.
- `network`: topology to be used.
- `dist`: statistical distribution used to generate the connections' bandwidth.
- `tempsVolta`: Inter Arrival Time
- `exp`: parameter to generate the connections' duration.

The simulations consists in fixing all these parameters while changing only the connections' size (`tamany_con`) per each connection. This is the way to obtain the BP in exactly the same network conditions for the different types of allocation strategies that are available.

3.2. Network Topologies

A key parameter of our simulation is the network topology. We have to bear in mind that we are simulating the BP in a continental optical network while using different spectrum allocation strategies. In this thesis we have studied two basically continental network topologies: National Science Foundation Network (NSFnet) for the USA network and the European Optical Network (EON) for the European network.

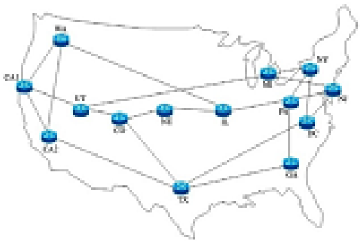

Figure 4: NSFnet topology

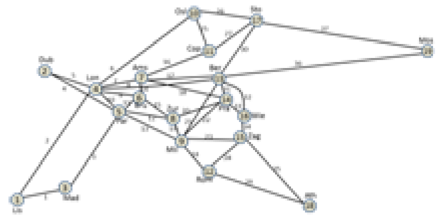

Figure 5: EON topology

NSFnet: The NSFnet topology (Figure 4) consists of 14 nodes and 21 links. It represents the USA's continental network.

EON: The EON topology (Figure 5) consists of 19 nodes and 37 links. It represents the European continental network.

3.3. Connection parameters

In this thesis we are considering three different types of connections regarding the strategy to allocate them in the spectrum, which can go from a Fixed-Grid manner (that is dividing the spectrum in 4 and 5FS blocks) to Flex-Grid.

Although it is evident that there are basic differences between these three network configurations, there are some parameters that are treated in the exact same way by all these configurations as they are the ones that define the basic elements of a connection. On the other hand, the network allocation strategy affects mostly the way that we are going to set the connections within the spectrum. Firstly, let's analyse the common elements:

3.3.1. Defining the route

We have widely explained that the purpose of this thesis is to analyse the BP of a spectrum in function of the allocation strategy followed. Notwithstanding the usual treatment of the spectrum we have been using, by considering it as an independent being, from now on, we have to bear in mind that in this thesis we are going to test a large number of spectrum slots, which will represent the resources that we have between every two pairs of nodes of the studied optical network. For that reason, we will have as many spectrum instances as possible routes are offered by this network.

Once we know what the spectrum represents in network terms, it is obvious that every single connection will follow a concrete path. Taking that into account, we will have to assign a node of the topology (remember section 3.2) as the source of this path and another one as its destination. The selection of these origin and destination nodes will be done randomly (uniformly distributed) so as to guarantee that, a priori, we are generating random routes that will let us do a fair simulation. It is clear that every path needs to have an origin and a destination, but this route isn't finished once these two elements are selected: going from one node to another could be done in several ways as we have multiple choices (nodes) to conform our final route. Therefore, the way these other nodes are selected is done following a concrete criterion: the Dijkstra's algorithm. The Dijkstra's algorithm is a method from graph theory that basically finds the shortest path between two nodes; in our case, this means that by using the previously given source and destination this algorithm will give us the nodes of the topology that we will have to use in order to define the path of our connection, which will be as short as possible.

3.3.2. Duration of the connections.

Apart from the path there is another key parameter that is assigned to each connection independently from the allocation strategy: the duration.

The duration follows a negative exponential distribution. As we have said in section 3.1, we have a key parameter in our simulator that is the `exp`: depending on the value that we decided to give to this parameter, the average value of the connections will change, which will have consequences in the OL. It is important to notice that we are talking about average duration; this is because the duration that we generate is different for each connection due to its dependency on a random parameter. In fact, the randomness of the connections' duration justifies the fragmentation of the spectrum, which leads to the BP, as the incoming and the departing connections are not synchronized.

3.4. Fixed-Grid strategy

When using the blocks of 4 or 5FS to allocate every single connection there appears a first problem: what is required to be done when a connection has more bandwidth than these prefixed 4 or 5 FSs? Let's find out the solution.

3.4.1. Fixed-Grid strategy: connection allocation

Firstly, in order to illustrate this problem we will use the following figures:

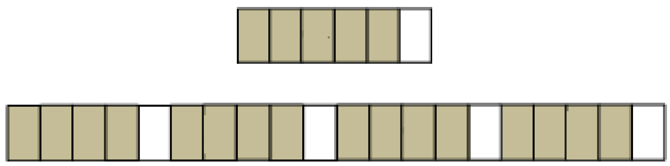

Figure 6: Incompatibility between a connection larger than 4FS and a 4FS strategy spectrum

In the Figure 6 it is seen that in a 4FS Fixed-Grid strategy the connections larger than 4FS (exemplified with the top figure of the Figure 6) do not fit the spectrum. Exactly the same happens when the strategy consists in fixing the spectrum allocation to 5FS. As a result, more than one spectrum assignment (also called subconnections) will have to be used to allocate those larger incoming connections. This phenomenon is shown in Table 3:

Connection size (FS)	Assig. spectrum (FS)		Free spectrum (FS)	
	4FS strat	5FS strat	4FS strat	5FS strat
1	4 (+1 GB)	5(+1 GB)	3	4
2	4 (+1 GB)	5 (+1 GB)	2	3
3	4 (+1 GB)	5 (+1 GB)	1	2
4	4 (+1 GB)	5 (+1 GB)	0	1
5	8 (+2 GB)	5 (+1 GB)	3	0
6	8 (+2 GB)	10 (+2 GB)	2	4
7	8 (+2 GB)	10 (+2 GB)	1	3
8	8 (+2 GB)	10 (+2 GB)	0	2
9	12 (+3 GB)	10 (+2 GB)	3	1

Table 3: Spectrum assignment model for 4FS and 5FS strategies

The solution proposed to solve this problem is to do a partition of the connection. In fact, this is the only way to allocate the connection in more than one spectrum assignments that will make it possible to serve the incoming connection without losing part of the required information. When a connection size is larger than these 4 or 5FS spectral subconnections we decided to split this connection. So now it is important to explain the criterion used in order to do these partitions.

3.4.2. Fixed strategy: connection partition

In this section we are going to explain the criterion that we have used in order to split a connection when using the strategies of 4FS and 5FS allocation respectively.

Connection size (FS)	Subconnection 1(FS)		Subconnection 2 (FS)		Subconnection 3 (FS)	
	4FS strat	5FS strat	4FS strat	5FS strat	4FS strat	5FS strat
5	4	-	1	-	-	-
6	4	5	2	1	-	-
7	4	5	3	2	-	-
8	4	5	4	3	-	-
9	4	5	4	4	1	-

Table 4: Partition strategy results

In Table 4 it can be seen that for both strategies we have decided to do a partition where fully spectral occupied subconnections are obtained. This means that the partition of the connection is done preserving always a subconnection of 4FS and 5FS respectively; consequently, we obtain a fully occupation of the subconnection instead of having multiple subconnections with free FSs. Now, we have to widely analyse the main reason why we have decided to use this partition strategy:

Maximising the fully spectrum occupation:

As we have explained, we are using this strategy mainly because we have decided to maximise the fully occupation of the subconnections (as seen in Table 4). The reason why we have used this criterion is that it is preferable to have an entire occupied subconnection, and therefore another one spectrally less used, in terms of both efficiency and BP. For both parameters, the reason that explains this criterion is the reallocation policy: this policy will be widely explained in section 3.6.1; nonetheless, we can anticipate that it consists basically on occupying the free FSs left by previous connections (in the subconnection that they occupy) to allocate those incoming connections whose size fits in this free space. Because of this reallocation policy we can assure that we will reuse spectrum that firstly was thought to be occupied by only one connection, which reduces the spectrum occupation, having a positive impact on the BP. This would also happen doing another partition strategy as the reallocation would be also possible. The fact is that reallocation is not a usual phenomenon (as we will see when analysing the simulations' results) so our aim is to try to make this phenomenon more usual; in order to do so, having subconnections with very little spectrum occupation makes easier a possible reallocation as we will have more surplus spectrum than in another strategies. Moreover, as we have explained in the theoretical background, using the fixed spectrum allocation leads to less fragmentation and, thus, to have less BP. With this strategy we are forcing to have a majority of connections (after being split) with exactly the same size of the subconnection strategy, increasing consequently the probability of finding an appropriate space in the spectrum. On the other hand, we will increase the efficiency as the subconnections will be more used than in the case when we are not doing reallocation having as a result more occupied spectrum per subconnection. To sum up, this strategy allows us to increase the reallocation of the used spectrum and therefore to take advantage of the benefits offered by this strategu. In addition, we will create a majority of connections with the size of the strategy, which is beneficial because it reduces the fragmentation.

3.4.3. Fairness in a partition

After explaining the partition strategy, we have to consider some aspects that we must take into account so as to do a fair comparison with the Flex-Grid case (where no partition is needed). In our code, once the partition is done, every subconnection does the same process: a route and a duration will be assigned to each one of them. These parameters were the common aspects for every connection regardless of the spectrum assignment model, as it has been explained in section 3.3. The point is that in order to guarantee that in a Fixed-Grid network the original connections (before the partition) have the same treatment that they would have in a Flex-Grid network model, we have assigned to each of its subconnections the same origin and destinations nodes and also the same duration. In addition, in the case of the route, we have decided to use this criterion not only due to the fact that it allows a fair comparison with the Flex-Grid case but also because of a practical reason: we cannot split data that is requested in a particular point and send part of it to another destination. That would lead to a loss in the data, and it would have even worse effects than blocking the connection.

3.5. Statistical distribution

In the previous sections we have explained what to do when the connections' size is larger than the one fixed by the spectrum allocation model of the network. This happens because we generate the bandwidth of every connection randomly; in function of the statistical distribution used we will have to do more partitions as the distribution could generate more connections with a higher bandwidth. Therefore, it is clear that the statistical distribution selected will affect to the final results.

In this project we have used three types of different statistical distributions in order to be able to test the performance of the programme under these different statistical conditions, especially in terms of BP. Let's now introduce these statistics:

- Uniform: When using a uniform statistical distribution we will have pretty much the same amount of connections of each bandwidth.
- Gaussian: So as to compare the performance with the uniform distribution we decided to choose a Gaussian distribution. Firstly, let's have a look to the Gaussian pdf:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

Analysing the pdf we can deduce that the basic parameters of the function are the μ (mean value) and the σ (typical deviation). The Gaussian distribution that has been used in our simulations has the following basic parameters:

- $\mu = 5$
- $\sigma = 2.5$

We decided to use this concretely Gaussian distribution so as to obtain a majority of the connexions with a bandwidth of 5FS. Thus, we reduce the fragmentation of the spectrum (as the more probable values of bandwidth will have a more reduced range around the mean value) in order to obtain a better performance in terms of BP. We will see if this theoretical prevision is accomplished when analysing the results in section 4.

- Beneficial Gaussian: Finally, we wanted to find out a configuration that shows a clearly better performance for the Fixed-Grid strategy than for the Flex-Grid model in terms of BP. The distribution that was used was a variable Gaussian with a low typical deviation:

Gaussian beneficial 1		Gaussian beneficial 2	
μ	4.5	**μ**	5.5
σ	1.25	**σ**	1.25

Table 5: Gaussian beneficial parameters

Using this double Gaussian we can take profit from both strategies where 4FS and 5FS are used. The idea is to have most of the connections with these sizes respectively, so we can reduce the fragmentation and also take advantage of the fact that having connections with the same size of the subconnection is beneficial when it comes to BP as the majority of connections will fit perfectly the spectrum. We will test if this theory is valid in section 4.

3.6. Assignment policy: reallocation, allocation and tear down

As we have constantly explained in the entire thesis the assignment model depends on the model of network chosen; that is, the Fixed-Grid strategy (4 or 5FS policy) or the Flex-Grid one.

In our programme we look for a place in the spectrum where the current connection fits. Nonetheless; firstly, we try to reuse the free spectrum of those connections that do not fulfil the entire subconnection capacity: that is what is called the reallocation policy.

3.6.1. Reallocation policy.

The reallocation policy consists in taking profit from those subconnections that do not have the spectrum fully occupied, that happens every time that a connection has to be split in different subconnection (remember Table 4). This remaining spectrum can be used to allocate other connections and, therefore, increase the efficiency of that concrete subconnection (as we will be using more spectrum usefully) and reducing the global spectral occupation which will lead to have less BP (our final objective). Nonetheless, we cannot use the reallocation without specifying previously some considerations:

- To be in a fixed allocation strategy (i.e. 4FS or 5FS): Evidently, the reallocation policy can only be used when we have connections that do not occupy entirely the spectrum resources offered to them. The main point of the Flex-Grid strategy is that it has an excellent efficiency (remember Table 2) the reason was that in this strategy just the spectrum that is needed is used, so this strategy cannot apply reallocation: spare spectrum won't be generated.
- The connection must not be of maximum size: This condition applies when we have bandwidths of 4 and 5FS respectively. We have to bear in mind that all this process begins once the partition strategy has been done. The reason is that the connections that are of maximum size will never be able to occupy the spectrum of an uncompleted subconnection, simply because there cannot be enough space for them. This leads to another condition: every subconnection must fit completely in the remaining space of the uncompleted subconnection that we want to reuse. Consequently, we cannot do another partition of the connection once we are trying to allocate it. We have decided to do so because the complexity of the programme would be clearly increased while; on the other hand, the gain obtained in terms of the number of connections reallocated is negligible.
- Route's coincidence: This is the most important condition. We cannot use an incomplete subconnection to reallocate a connection whose route is not the same. If the routes are not the same it is evident that reallocating the connection is not useful as we will be sending the connection to a destination where it is not needed and that would be an important mistake, inasmuch as it would be equivalent to losing the connection.

Only if all of these conditions are accomplished we would be able to reallocate a connection. Therefore, the number of reallocations obtained is not very large. The route's coincidence is essential, because without this condition we would be reallocating a great number of connections wrongly and these would lead us to excellent, but wrong, results.

The connections that accomplish these conditions and are reallocated are linked with the connections reused. This link would be useful in terms of timing and spectrum occupancy as we will explain in following sections.

3.6.2. Allocation policy

If the reallocation has not been possible then the connection starts the allocation strategy:

3.6.2.1. Spectrum's treatment

In this section the procedure followed to allocate a connection in the spectrum will be described. The strategy changes depending on the allocation model. So we will describe both the strategy based on the Flex-Grid model and the one based on Fixed-Grid one.

3.6.2.1.1. Flex-Grid strategy

In the case of a Flex-Grid allocation strategy we will have to look for an appropriate spectrum space in the link used by the connection. This space has to be large enough to allocate the connection bandwidth and the GB FS. Once the space has been found we have to mark the reference FS from which we will allocate the connection and finally occupy the spectrum from this reference to the exact size of the connection. On the other hand, if any space in the spectrum is found we will have to block the connection.

3.6.2.1.2. Fixed-Grid strategy

In this case the allocation process is almost the same as in the Flex-Grid case. The main difference is what we have been explaining during the entire thesis: in a fixed strategy we will use a fixed number of FS per connection (4 or 5 depending on the case) regardless of the connection's real size. So this will be the principal change: independently of the connections' size we will have to look always for a space in the spectrum of 4 or 5FS. Once the space has been found we have to mark the reference FS from which we will allocate the connection and finally occupy the spectrum from this reference to the predetermined size of the strategy followed. On the other hand, if any space in the spectrum is found we will have to block this connection.

In this case, we have to prepare the connections that have been allocated in the spectrum for a possible reuse of its remaining spectrum (if there are free FS). In order to do so a variable that controls the remaining space in these connections is used. Every connection that tries to be reallocated will compare its bandwidth with the value of this variable, if the bandwidth is equal or lower than the value of the variable the reallocation would be done.

3.6.3. Temporal treatment: tear down management

We have explained how to generate and allocate the incoming connections, so it is time to analyse also the way they are torn down: we are going to explain the temporal evolution of the programme.

As it has been explained in section 3.3.2 every incoming connection will have a random duration assigned (that follows a negative exponential distribution in our case). Connections' duration is reduced during the execution until they are completed. This is the system that has been used to do so:

An essential parameter to manage the time in this simulator has been the variable `tempsVolta`. `tempsVolta` is the IAT, which is the time between arrivals. During the entire project we have considered our IAT to be following a Poisson distribution with mean value equal to 1:

```
tempsVolta=1
```

The reason why it is so important to work with that value is that in our simulation each incoming connection is treated initially separately: every connection will pass through a process of generating its route and duration, then the partition (if needed) and finally trying the allocation.

So these are the main functions that a connection will have to do during its life in this algorithm; in fact, once it has been allocated, it would experience a passive process that would consist in being part of a reallocation (if possible) and progressively reducing its duration, as the simulation advances, to finally be torn down. So, the way we decided to manage the pass of the time and linking it with the arrival of new connections was the IAT. The algorithm consists in a loop that has the size of the number of total connections of the simulations, so every time that the whole process is done by a connection we have to deduct the IAT to the duration of the ongoing connections, this way we are considering the pass of the time and simultaneously we are preparing the code for the arrival of a new connection: IAT is the time between connections, so once it is considered (when reducing the duration specifically by its value) a new connection must arrive, which in terms of code would mean that another iteration starts and a new connection begins its process.

Following the explained procedure, when a connections' duration finishes it is time to tear down the connection. A priori when a connection dies the spectrum that it was occupying must be released. This is what happens when using a Flex-Grid strategy. On the other hand, when we use a Fixed-Grid model we have to bear in mind an essential consideration: the reallocation. If a connection has been reused, we cannot release the spectrum until the duration of both the original and the reallocated connection are over. The reason is that independently of the size of the connection, we always occupy a fixed spectrum (we are in the fixed strategy); therefore, we cannot release the spectrum if the reallocated connection is still going on. What we will have to do in this case is upload the free space of that concrete connection that is now prepared to be reused. Only when all the connections associated to a concrete spectrum space are finished we will release this spectrum.

The treatment of the time is extremely important; if it is processed wrongly we could obtain results that can go from extremely good to really bad, and neither case is correct. We must assure that time does not pass too quickly or too slowly provoking a spectrum under-occupied or over-occupied, respectively.

3.7. Obtaining results

The main result that we are going to obtain with the programme is the BP value. So let's analyse firstly what the BP is and how we are going to calculate it.

The BP is the probability that has a connection of being blocked when it is send to the network. As we have explained 3.6 this happens when we cannot reallocate nor allocate the connection in the current network spectrum. So as to find out this value we will compute the total amount of blocked load, the complete offered load and finally calculate its ratio. This is the BP's expression:

$$BP = \frac{Blocked\_Load}{Offered\_Load}$$

In addition, there are some considerations that have been implemented when it comes to calculate the BP. These considerations will be divided between the ones done to preserve the justice of the system and others done in order to benefit the global system by reducing the BP. In the following subsections, 3.7.1 and 3.7.2 we are going to comment them.

3.7.1. Fairness considerations

In previous sections we have widely explained how to manage the partition of a connection in a Fixed-Grid allocation strategy (section 3.4.2) and how to allocate them (section 3.6.2.1.2). When computing the BP we have to consider some premises to obtain as fairly as possible this value for both the Flex-Grid and the Fixed-Grid strategy. In a Flex-Grid strategy when a connection is blocked, its FS of information is not sent. Usually the connections that are blocked are the ones that have a larger size; the reason is simple: the BP is mostly consequence of the spectrum's fragmentation, therefore it is more difficult for a large bandwidth to find a space where being allocated as they need bigger spaces. Therefore, when a large bandwidth connection is blocked in a Flex-Grid strategy we will block the entire associated load. However, in a Fixed-Grid model a connection of the same size could have been previously split, so there is the possibility that a part of the connection could have been blocked while another one could have been correctly set, reducing this way the amount of load blocked (as only a subconnection has been blocked while in the FG model the whole connection has been discarded). In order to be fair this should not happen; so if in a Fixed-Grid strategy a connection was split and if anyone of its subconnections was blocked, automatically all the other subconnections would have to be also blocked.

To sum up, applying this criterion is essential because it guarantees the fair comparison between the Flex-Grid and Fixed-Grid case in terms of BP; which is vital in a thesis where the main aim is to compare, precisely, the BP values for these different allocation strategies.

3.7.2. Improving the conditions

Not only have we applied considerations to equalize the conditions of the comparison between strategies but we have also implemented other policies that will lead the system to decreasing the BP for both of the strategies used. In this section we are going to explain which these beneficial considerations are:

- Reallocation policy (explained widely in 3.6.1): this is a consideration that applies only for the fixed strategies. Based in reusing the uncompleted subconnections, which leads to reducing the occupancy of the spectrum and therefore reducing the BP.
- Full routes: when a route of the network is highly used and no more connections can be allocated in it, we decided to erase it from the possible routes that a new incoming connection could define (remember section 3.3.1). This measure prevents new connections from trying to allocate their bandwidth in an over-occupied spectrum; thus reducing their probability of being blocked.

4. Results

This section presents the results obtained by our programme in terms of BP depending on: the statistical distribution, the network topology, the allocation strategy and the OL.

The BP results are going to be presented by graphs where the BP depending on the OL is compared for the different allocation strategies. It has to be highlighted that the Offered Load values shown in the results represent load per link, considering that the maximum load would be given by:

$$MaxLoad = \frac{160}{NHops} * \frac{\overline{BW}}{\overline{BW}+1}$$

where $\overline{BW}$ is the average connection BW and NHops correspond to the average number of hops per connection. Taking into account that there is 1 GB FS allocated to each connection, a perfectly loaded link would carry MaxLoad FS, so the Offered Load values are normalized respect to that optimum in the results graphs.

In the following subsections we are going to show these graphs as well as some important elements that will prove some of the theoretical considerations explained in the previous sections. The results are presented in different subsections in function of the statistical distribution.

4.1. Results for the Uniform distribution

To begin with let's analyze the profile obtained for our programme with the uniform distribution:

Allocation	Conn	Sub	1FS%	2FS%	3FS%	4FS%	5FS%	6FS%	7FS%	8FS%	9FS%
FG	10000	10000	11.25	11.02	11.03	11.04	11.08	11.73	10.73	11.1	11.01
4FS	10000	16696	13.4	12.95	13.24	60.39	-	-	-	-	-
5FS	10000	14432	15.34	15.59	15.21	15.32	38.51	-	-	-	-

Table 6: Allocation results for uniform distribution

In the case of the FG allocation strategy we can observe clearly that the programme applies a correct uniform distribution: all the possible sizes are obtained, pretty much, with the same probability. On the other hand, the rest of allocation strategies show how the partition strategy works: we can see that the number of connections and subconnections is not the same; this is because when the bandwidth exceeds the prefixed spectrum space the connection is split, as we can see in the percentages finally obtained. Moreover, this results show that the partition strategy has worked correctly as we obtain a majority of connections of 4 and 5FS for the respectively strategies (see section 3.4.2)

In section 3.7.2 we have explained some conditions to improve the system's performance in terms of BP. Here we have the results obtained for these conditions:

Allocation	Erased Routes	% reallocations
FG EON	519	-
FG NSF	426	-
4FS EON	888	5.97
4FS NSF	631	8.07
5FS EON	821	10.32
5FS NSF	570	13.76

Table 7: Results of the beneficial decisions for uniform distribution

For both the NSF and EON topologies the pattern obtained is almost the same. When it comes to the erased routes we can observe that we would discard more in the fixed case. That happens because we only discard a route when it is completely used: in a Flex-Grid strategy, useless voids appear because of the spectrum fragmentation; these voids prevent the spectrum from being completely used and consequently it is more difficult to discard a route. The discarded routes are larger for the EON case because there are more nodes, and consequently more possible routes to be eliminated. In terms of reallocation we can reallocate more in the 5FS strategy because we will have less connections of maximum size (see Table 6Table 8) and this is one of the conditions that must have a connection for not being reallocated (see 3.6.1). Finally, there is more reallocation in the NSF topology because there are less nodes and therefore it is more probable for the connections to have a coincident route, which is a basic condition so as to reallocate (see 3.6.1).

Once explained this preliminary results, let's analyse the BP obtained per OL:

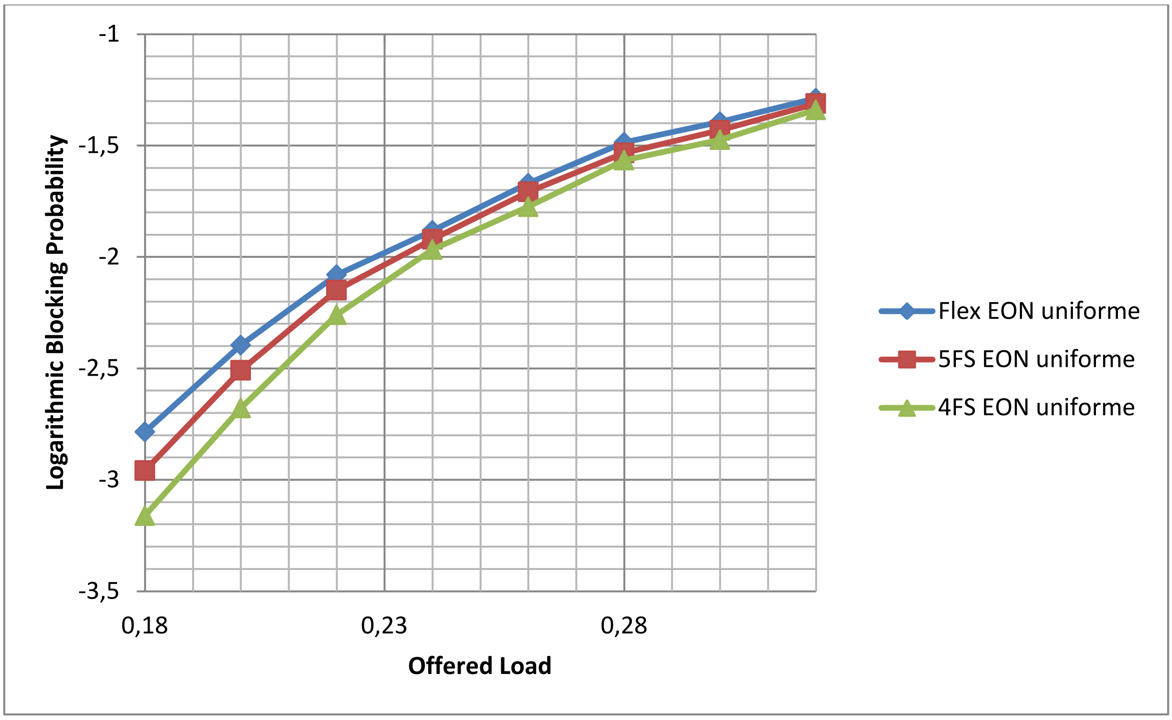

Figure 7: BP comparison in an EON topology for a uniform distribution

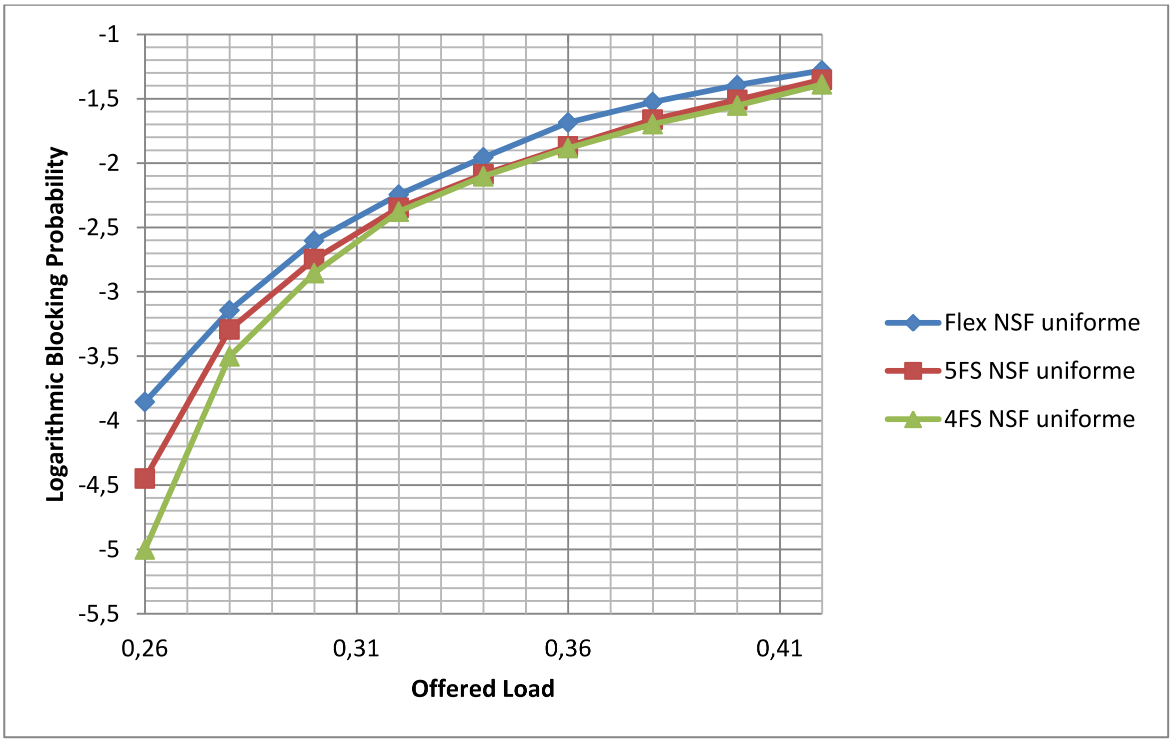

Figure 8: BP comparison in an EON topology for a uniform distribution

In this graphs we can observe almost the same pattern: the BP is better when the allocation strategy is fixed to smaller sizes. In addition, we can conclude that when it comes to BP it has a greater impact reducing the fragmentation rather than reallocating more connections: in Table 7 we can see that we have more reallocation in the 5FS than in the 4FS model while the BP is greater in the 5FS case; the reason is the fragmentation, which is lower in the 4FS strategy as there are a more 4FS connections in the 4FS model than the number of 5FS connections that the respectively strategy has (see Table 6). Thus, the majority of connections fit perfectly the blocks that divide the spectrum provoking a decrease in the fragmentation.

Results summary for EON topology

Allocation	EC	EC' (realloca)	Gain EC (wrt FG)	OL (BP=1%)	Gain BP (wrt FG)
FG	0,785	0,785	-	0,228	-
4FS	0,577	0,614	27.85%	0,238	4.38%
5FS	0,57	0,637	23.23%	0,233	2.3%

Table 8: Summary for the EON topology (uniform)

In Table 8 the effect of the reallocation in terms of efficiency is pointed out. Regardless, our main interest was comparing the trade off efficiency-BP. We can observe that the gain obtained is better when it comes to efficiency rather than the obtained for the BP. We will see if in following statistical distributions the tendency changes.

4.2. Results for the Gaussian distribution

To begin with let's analyze the profile obtained for our programme with the Gaussian distribution:

Allocation	Conn	Sub	1FS%	2FS%	3FS%	4FS%	5FS%	6FS%	7FS%	8FS%	9FS%
FG	10000	10000	6.03	7.25	11.6	15.83	17.42	16.19	12.03	7.6	6.04
4FS	10000	16496	14.21	14.2	14.12	57.44	-	-	-	-	-
5FS	10000	14156	15.94	13.64	13.26	15.59	41.54	-	-	-	-

Table 9: Allocation results for Gaussian distribution

In the case of the FG allocation strategy we can observe clearly that the programme applies a correct Gaussian distribution of mean value μ=5. As in section 4.1, we can see how the partition strategy works: the strategy has worked correctly as we obtain a majority of connections of 4 and 5FS for the respectively strategies (see section 3.4.2). Moreover we can see that the purpose (that was obtaining a majority of connections of 5FS) has been fulfilled.

In section 3.7.2 we have explained some conditions to improve the system performance in terms of BP. Here we have the results obtained for these conditions:

Allocation	Erased Routes	% reallocations
FG EON	480	-
FG NSF	335	-
4FS EON	818	6.6
4FS NSF	493	8.95
5FS EON	762	9.51
5FS NSF	493	12.72

Table 10: Results of the beneficial decisions for Gaussian distribution

For both the NSF and EON topologies the pattern obtained is almost the same. When it comes to the erased routes we can observe that we would discard more in the fixed case. That happens because we only discard a route when it is completely used: in a Flex-Grid strategy, useless voids appear because of the spectrum fragmentation; these voids prevent the spectrum from being completely used and consequently is more difficult to discard a route. The discarded routes are larger for the EON case because there are more nodes, and as a result more possible routes to be eliminated. In terms of reallocation we can reallocate more in the 5FS strategy because we will have less connections of maximum size (see Table 9) and this is one of the conditions that a connection must have for not being reallocated (see 3.6.1). Finally, there is more reallocation in the NSF topology because there are fewer nodes and therefore it is more probable for the connections to have a coincident route, which is a basic condition so as to reallocate (see 3.6.1).

Once explained this preliminary results, let's analyse the BP obtained per OL:

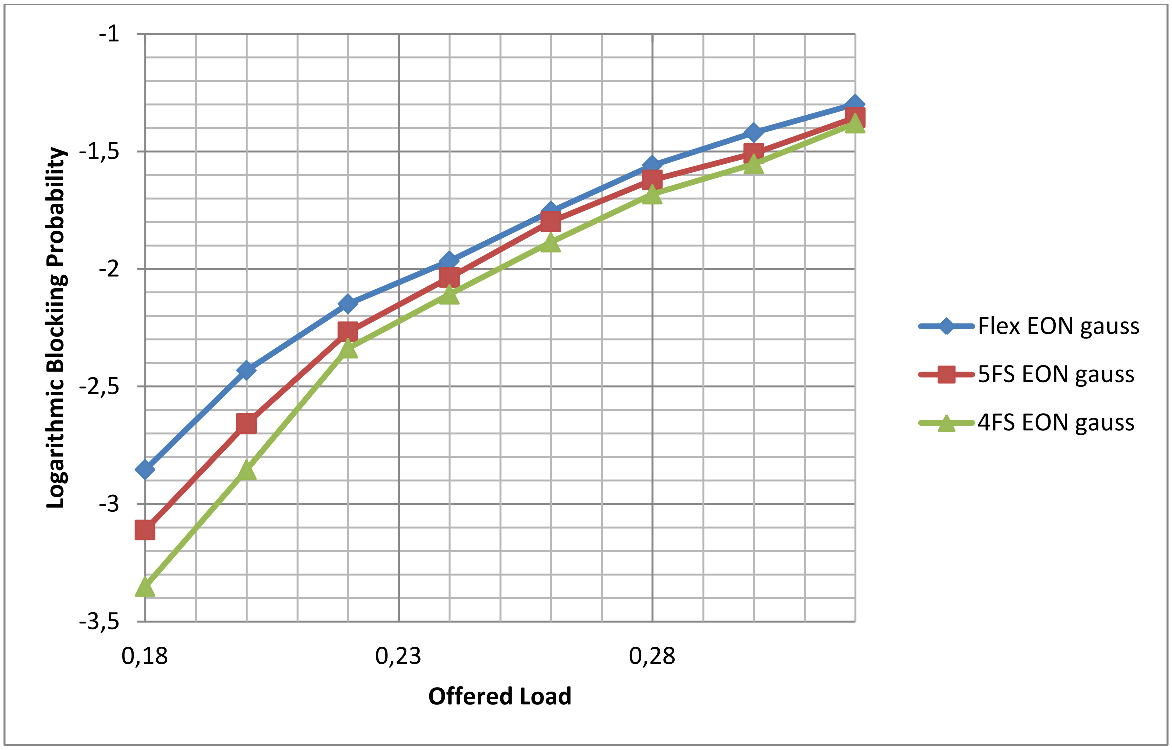

Figure 9: BP comparison in an EON topology for a Gaussian distribution

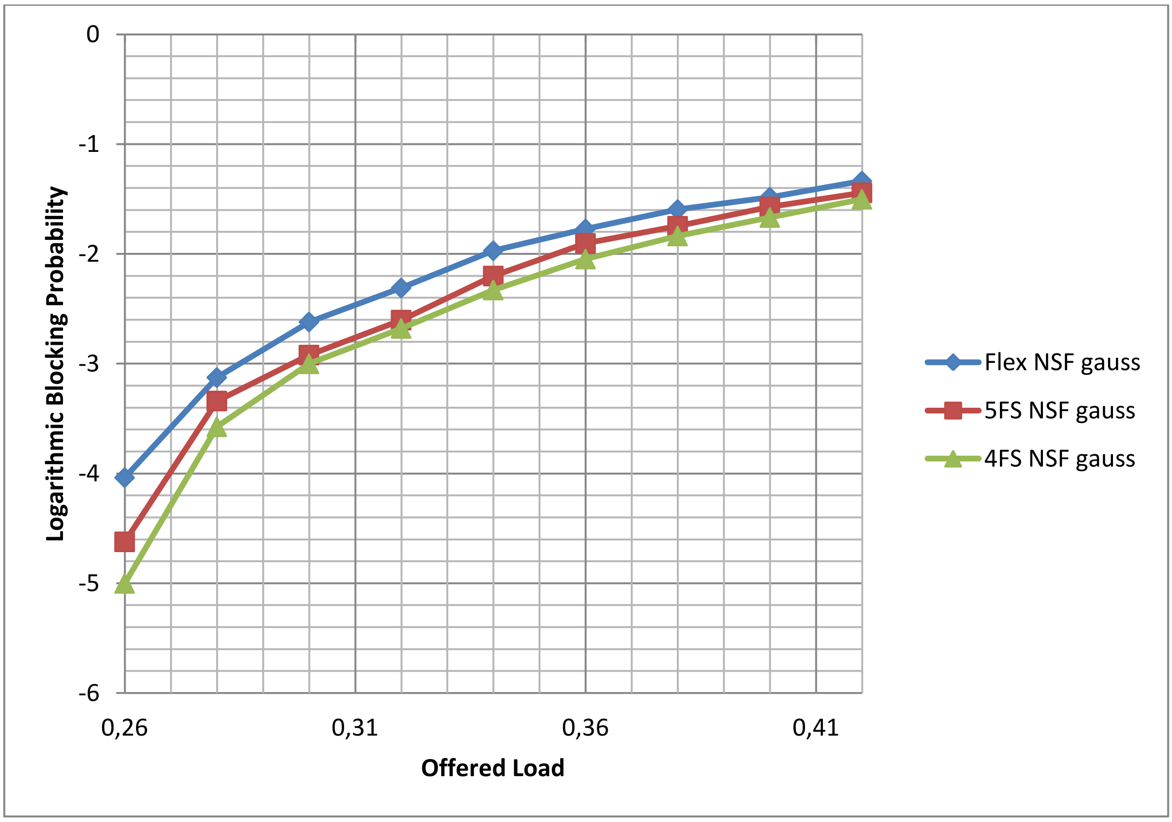

Figure 10: BP comparison in an EON topology for a Gaussian distribution

As we have commented in section 4.1 it is more relevant to have less fragmentation than the effect provoked by the reallocation since the 5FS reallocates more but 4FS obtain better results. In general, the pattern is slightly the same as the one obtained with uniform distribution but with general best results (lower BP). Let's analyse the summarised EON results:

Allocation	EC	EC' (realloca)	Gain EC (wrt FG)	OL (BP=1%)	Gain BP (wrt FG)
FG	0,798	0,798	-	0,236	-
4FS	0,629	0,673	18.57%	0,25	5.93%
5FS	0,588	0,65	22.76%	0,244	3.38%

Table 11: Summary for the EON topology (Gauss)

In Table 11 the effect of the reallocation in terms of efficiency is pointed out. Nevertheless, our main interest was comparing the trade-off efficiency-BP. We can observe that the gain obtained is better when it comes to efficiency rather than the obtained for the BP. However, we can observe a reduction in the Gain EC and an increase in the Gain BP, which means that we are closer to prove that using a FG strategy may not be as worthy as it is thought.

4.3. Results for the beneficial Gaussian distribution

To begin with let's analyse the profile obtained for our programme with the Beneficial Gauss distribution:

Allocation	Conn	Sub	1FS%	2FS%	3FS%	4FS%	5FS%	6FS%	7FS%	8FS%	9FS%
FG	10000	10000	0.23	1.93	9.03	22.56	32.43	22.59	9.25	1.77	0.2
4FS	10000	16547	19.55	14.44	10.78	55.2	-	-	-	-	-
5FS	10000	13480	17.72	7.81	7.92	17.05	49.47	-	-	-	-

Table 12: Allocation results for a beneficial Gaussian distribution

In the case of the FG allocation strategy we can clearly observe that the programme applies the specified variable Gaussian distribution. As in section 4.1 we can see how the partition strategy works: the strategy has worked correctly as we obtain a majority of connections of 4 and 5FS for the respective strategies (see section 3.4.2). Moreover we can see that the objective (which was to obtain a majority of connections of 5FS) has been reached for the 5FS model. On the other hand, we can observe that in the 4FS allocation strategy the chosen distribution provokes the presence of a lot of connections of 4 and 5FS. This important quantity of connections with a bandwidth of 5FS is pointed out by the great amount of final connections of 1 and 4 FS, which is consequence of the partition strategy used (see Table 4).

In the section 3.7.2 we have explained some conditions to improve the system performance in terms of BP. Here we have the results obtained for these conditions:

Allocation	Erased Routes	% reallocations
FG EON	480	-
FG NSF	335	-
4FS EON	676	8.16
4FS NSF	357	10.99
5FS EON	668	7.61
5FS NSF	389	10.33

Table 13: Results of the beneficial decisions for a beneficial Gaussian distribution

For both the NSF and EON topologies the pattern obtained is almost the same. When it comes to the erased routes we can observe that we would discard more in the fixed case. This happens because we only discard a route when it is completely used: in a Flex-Grid strategy, useless voids appear because of the spectrum fragmentation; these voids prevent the spectrum from being completely used and consequently it is more difficult to discard a route. The discarded routes are larger for the EON case because there are more nodes, and therefore more possible routes to be eliminated. In terms of reallocation the tendency changes, for the first time in this simulations we reallocate more in the 4FS strategy; the reason is that (as we have seen in Table 12) we have a lot of 1FS connections, which helps to reallocate as this type of connections have a lot of spare spectrum. As a result it would be easier for an incoming connection to fit in an ongoing connection: the reallocation increases.

Once explained this preliminary results, let's analyse the BP obtained per OL:

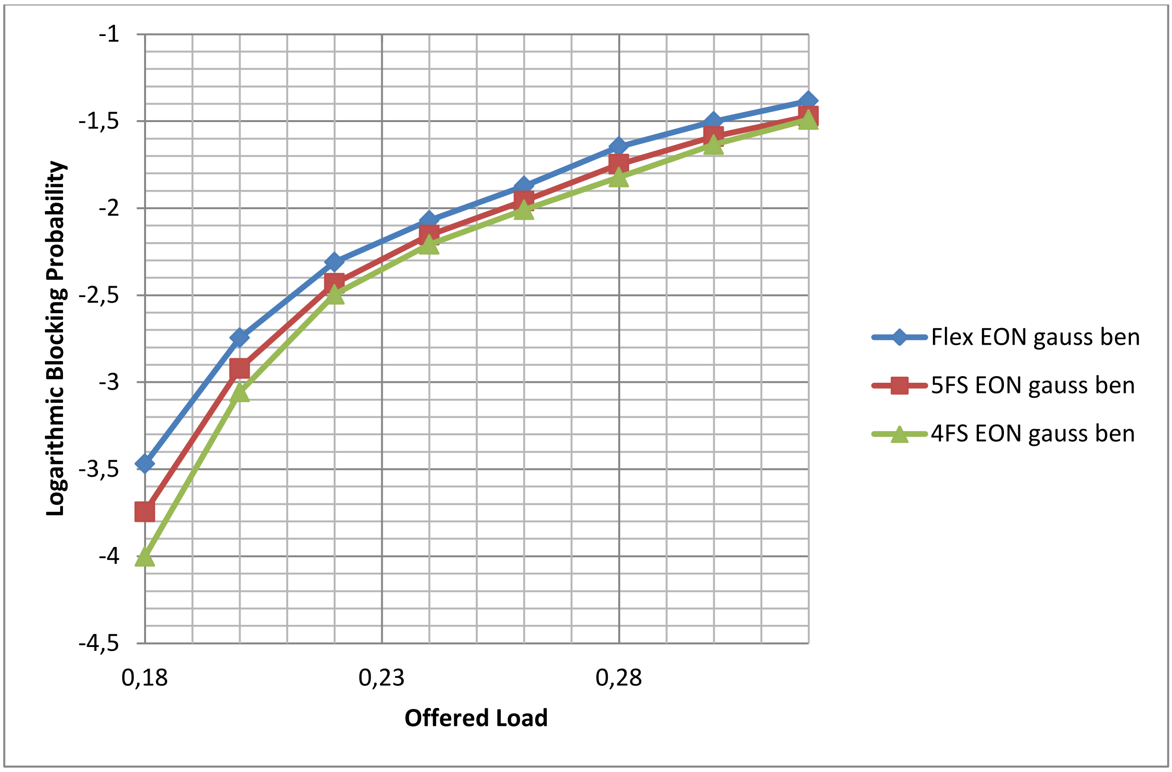

Figure 11: BP comparison in an EON topology for a Gaussian distribution

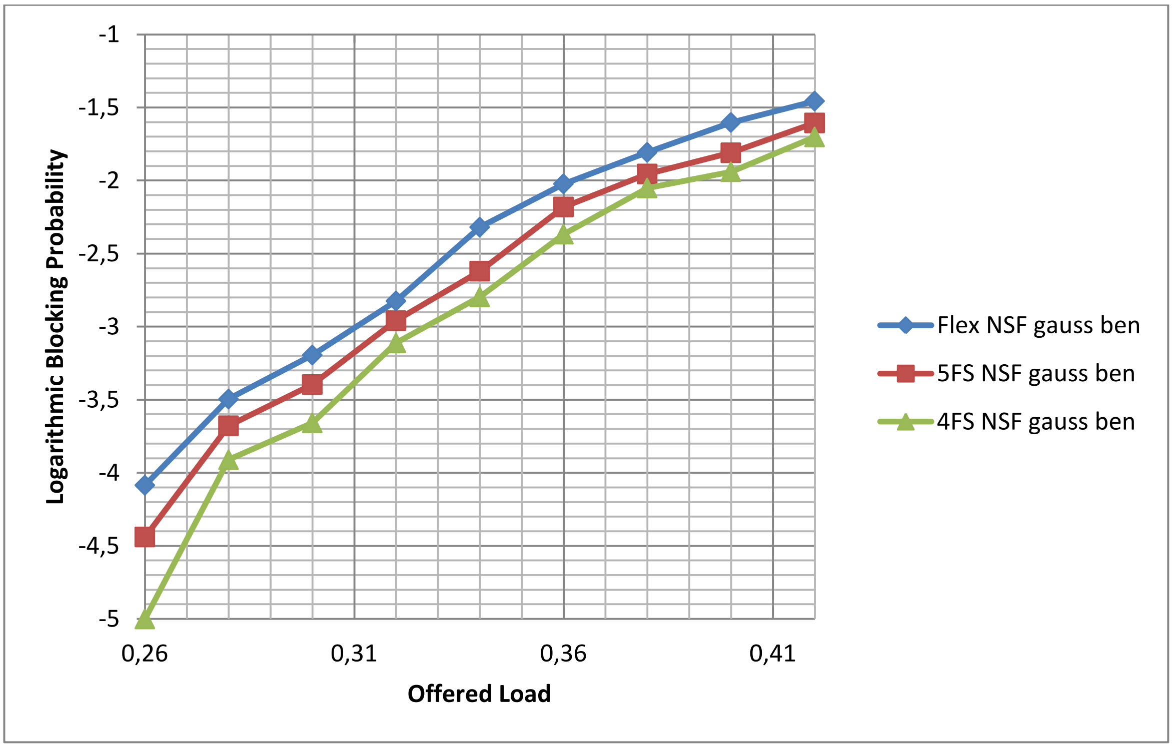

Figure 12: BP comparison in an EON topology for a Gaussian distribution

As we have commented in the section 4.1, it is more relevant to have less fragmentation than the effect provoked by the reallocation. In this case the 4FS strategy is better in both terms: the reallocation has increased until being higher than in the 5FS case and regardless of having less difference in terms of fragmentation (see Table 12, the difference between the number of 4FS and 5FS connections in the respectively strategies has been decreased) it is still clearly better for the 4FS model. This leads to really interesting BP results in this strategy. In spite of the fact that the pattern is slightly the same as the one obtained with uniform and Gaussian distributions: Fixed-Grid shows a better performance than the Flex-Grid when it comes to BP. Nonetheless, the results are extremely better in this case (not only for the 4FS model) and the differences between the Fixed-Grid and Flex-Grid cases are greater than ever before. To sum up, let’s analyse the summarised EON results:

Allocation	EC	EC’ (realloca)	Gain EC (wrt FG)	OL (BP=1%)	Gain BP (wrt FG)
FG	0,817	0,817	-	0,246	-
4FS	0,603	0,656	24.54%	0,262	6.5%
5FS	0,621	0,672	21.57%	0,256	4.06%

Table 14: Summary for the EON topology (beneficial Gaussian)

In Table 14 the effect of the reallocation in terms of efficiency is pointed out. Despite this fact, our main interest was to compare the trade-off efficiency-BP. We can observe that the gain obtained is far better when it comes to efficiency rather than the one obtained for the BP. However; the tendency changes, a reduction in the Gain EC and an increase in the Gain BP is pointed out, which means that we are closer to prove that using a FG strategy may not be as worthy as it is thought. Nonetheless, if we base the comparison in the trade off efficiency-BP the Flex-Grid performance is still widely better than the Fixed-Grid, but there are some considerations that must be taken into account to do a truly fair comparison. Now we are going to analyse them.

4.4. Final considerations

In the previous sections (4.1, 4.2, 4.3) we have seen how the network responds when applying different statistical distributions. The higher the beneficial distribution; the network can carry 6.5% more traffic in the Fixed-Grid case than in the Flex-Grid model, which represents a considerable gain. However, the difference with the efficiency gain is still important. In order to be completely accurate, there are some reasons that must be taken into account that suggest that a Flex-Grid performance is not as good as thought when compared to Fixed-Grid model:

- Potential capacity: the remaining spaces in some of the subconnections that have not been reallocated suggest that this free spectrum could be used to give response to a possible increase of the capacity needs of the user, that will represent using connections with more bandwidth. So we have a great potential in terms of spectrum that should not be underrated.
- Response to large connections: the results obtained have not shown one of the strongest points of the Fixed-Grid case, its performance with the larger

connections. Because of the partition policy, in the Fixed-Grid case the bigger connections could be managed as individual smaller subconnections that are easier to allocate. In the Flex-Grid case it is very difficult to find an allocation for these connections, which are usually blocked. In order to do a fair comparison, we decided to block every of the subconnections created from the same original connections only if one of them was blocked (section 3.7.1). If this criterion was not applied the BP would have been even better for the fixed model.

- Current infrastructure: the required infrastructure to deploy a Flex-Grid network is more difficult and expensive than the Fixed-Grid, which can use the current infrastructure. Nonetheless, these aspects won't be explained in this thesis.

Bearing in mind all these aspects, at least the worthiness of the Flex-Grid case could be doubted. It is evident that this kind of network is really useful when it comes to efficiency, but the OL that can be supported for the fixed model is higher and put in with the previous considerations; it equalises, pretty much, the performance of these two different models.

5. Budget

The elaboration of this thesis has consisted basically in the elaboration of a simulator as it has been pointed out during the entire document. Therefore, to make this economical budget we will only have to take into account the following items: the license of the software (Matlab in this case) and the human work of a junior engineer. The final cost analysis is shown in the following table:

Task	Weeks	Hours	Cost per hour (€)	Cost (€)
Planning	2	30	8	240
Analysis of the given resources	2	30	8	240
Programming the simulator	11	220	8	1760
Simulation and results	4	80	8	640
Redaction	3	50	8	400
Software	11	-	-	1000
TOTAL				**4280**

Table 15: Budget

6. Conclusions and future development:

The Flex-Grid optical networks are a hot topic in the optical technology's field. This type of networks has as the main characteristic the flexible use of the optical spectrum. In fact, it is a spectrum-efficient model because only uses the spectrum concretely needed for every single connection, which means that there is no spectrum wasted. Nonetheless, we have proved in this thesis that this networks lead to a considerable fragmentation of the spectrum. This fragmentation has as a consequence the apparition of some useless spectrum voids that provoke an increase of the BP. So, using a Fixed-Grid network, where this fragmentation does not appear, has been considered. We have tested the cases were the allocation is done by dividing the spectrum in prefixed 4 and 5FS blocks. This strategy has a lower efficiency as there are connections that will not occupy completely the spectrum offered by the fixed block. However; we have taken advantage of this drawback by using this spare spectrum spaces to reallocate new incoming connections, which have positive consequences for both the efficiency and the BP. On the other hand, this strategy allows the system to carry more OL than the Flex-Grid case. In fact, we have proved that we can increase until a 6.5% the offered load supported with a 4FS strategy in an EON topology with the appropriate statistical distribution. Moreover, the Fixed-Grid networks offer other advantages such as its performance with large connections (which is certainly better than in the Fixed-Grid case), the potential capacity in the subconnections' spare spectrum and its less complex infrastructure in the physical layer. All this evidences must be taken into account when it comes to evaluate the worthiness of applying a Flex-Grid network. The Fixed-Grid model presents a performance that can be put on the same level and that has an easier application, so it is a perfectly valid option. Finally, the future aim must be giving priority to some connections: in both strategies the connections which have a larger bandwidth are the ones that are usually blocked, this happens because it is more difficult to find in the spectrum a space large enough to allocate these connections. Therefore, the possibility of giving priority to allocate the connections that have a greater size should be considered in the future; because, for example, it is better to block a connection of 3FS rather than a one of 8FS as the load blocked is higher in the second case and a reduction of the BP would be obtained.

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Appendices (optional):

Glossary

EON: Elastic Optical Network

FS: Frequency Slot

BP: Blocking Probability

OL: Offered Load

WDM: Wavelength-Division Multiplexing

GB: Guard Band

NSFnet: National Science Foundation Network

EON: European Optical Network

PDF: Probability Density Function

IAT: Inter Arrival Time

FG: Flex-Grid

EC: Efficiency